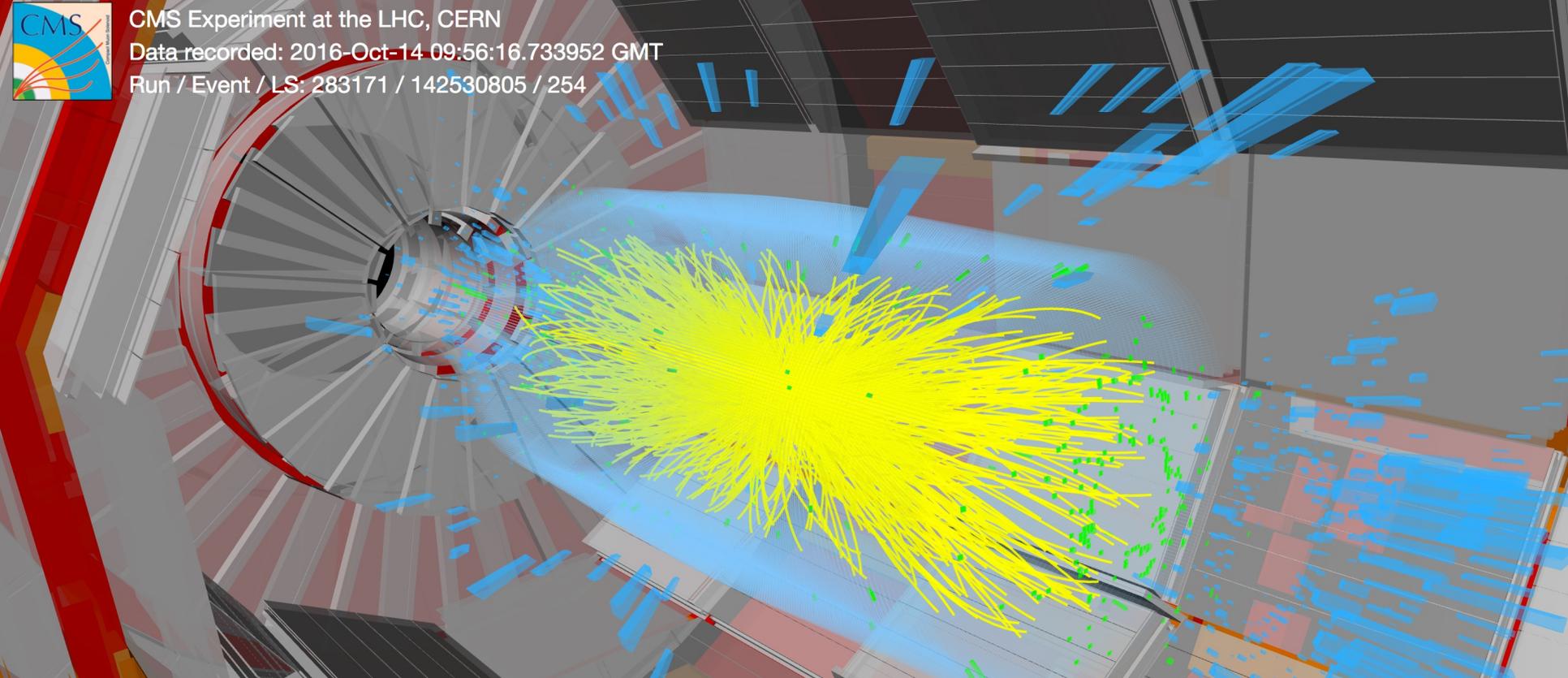




CMS Experiment at the LHC, CERN
Data recorded: 2016-Oct-14 09:56:16.733952 GMT
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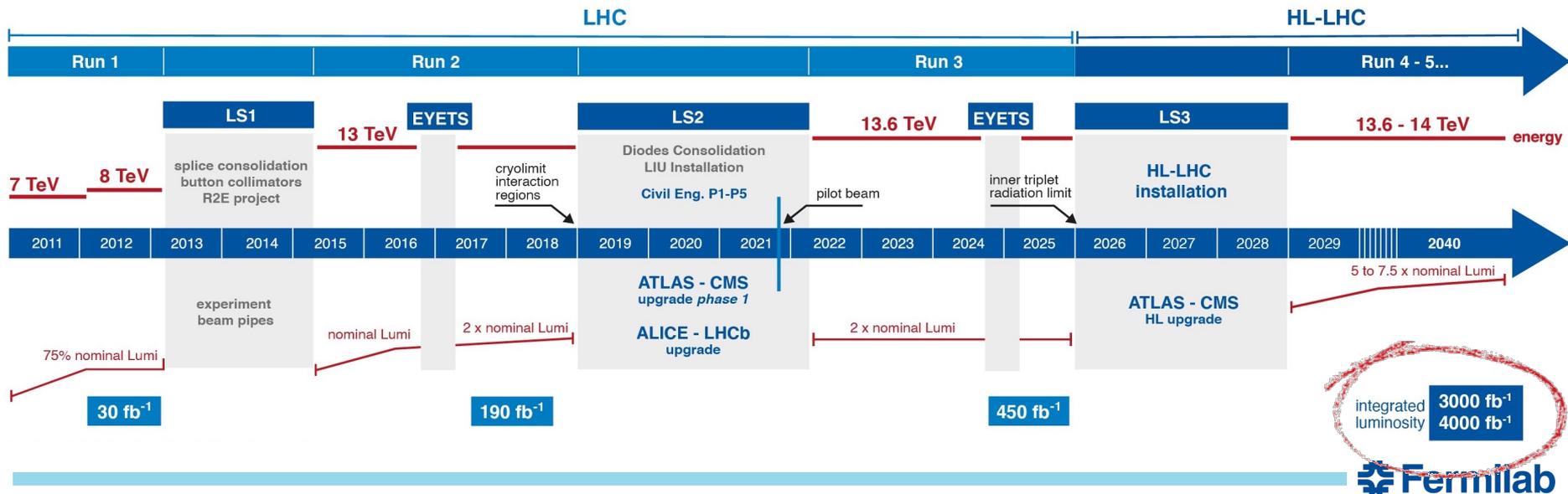
Physics at the High Luminosity LHC with ATLAS and CMS

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on behalf of the ATLAS and CMS collaborations
Snowmass Community Summer Study
July 23, 2022



High Luminosity LHC (HL-LHC)

- Broad physics goals
 - Search for **rare processes** and make **more precise** measurements
- **HL-LHC** collider upgrade will provide more data than ever
 - Up to ~20x more integrated luminosity than we have now, ~100x more than we had at the time of the Higgs discovery
 - Associated challenges: complicated environments (**high pileup**), more radiation damage to detectors



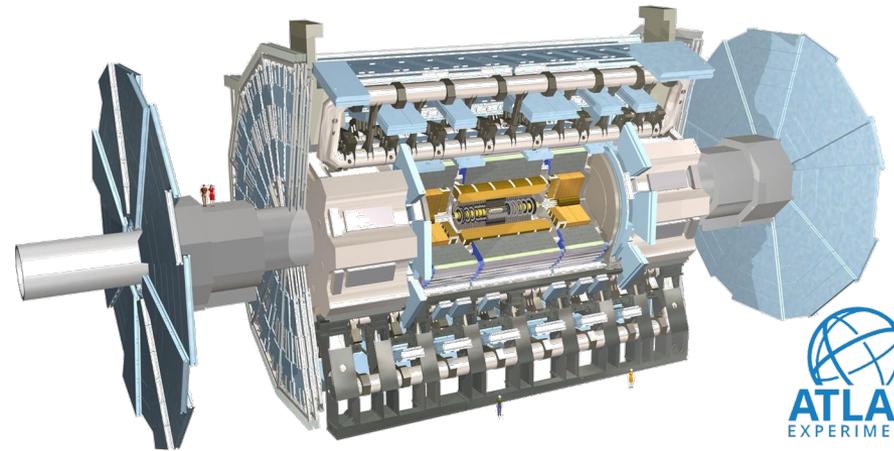
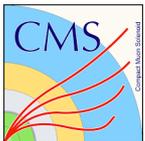
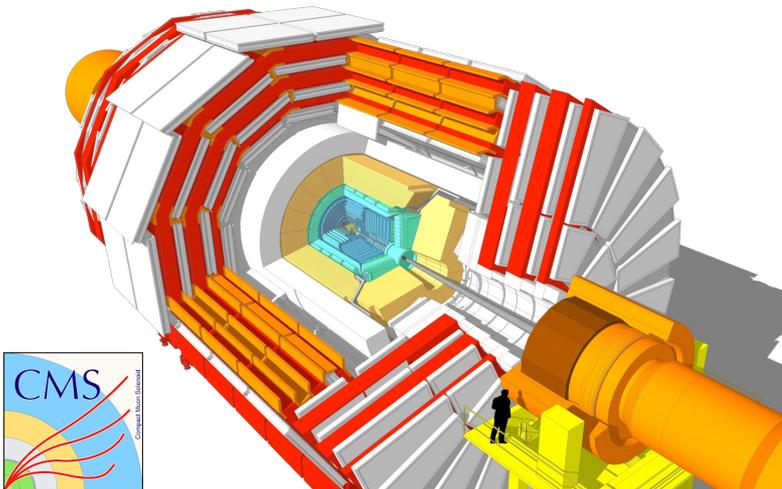
HL-LHC detector upgrades

CMS detector

- New: MIP timing detector, additional muon detectors
- Fully replaced: silicon tracker, endcap calorimeters, trigger
- Upgraded: barrel calorimeters, forward calorimeters, muon chambers

ATLAS detector

- New: high granularity timing detector, additional muon detectors
- Fully replaced: silicon tracker, trigger
- Upgraded: liquid argon (EM) and tile (hadron) calorimeters, muon chambers



(Some of the) Latest HL-LHC projections for Snowmass



Benefits from **luminosity**



Benefits from **detector upgrade**



Benefits from clever **algorithms**

Physics potential of the HL-LHC

- Overview in [ATLAS+CMS Snowmass white paper](#) (2022)
 - Includes results from [HL-LHC Yellow Report](#) (2019)
 - +28 **new projections** from the collaborations!
- Assumptions on uncertainties:
 - **Experimental** uncertainties reduced by $\sim \sqrt{\text{luminosity}}$
 - **Detector performance** as good or better than now, but with harsher pileup conditions
 - **Theory** uncertainties reduced by a factor of ~ 2

Physics potential of the HL-LHC

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Higgs boson Sapta's talk

Standard Model

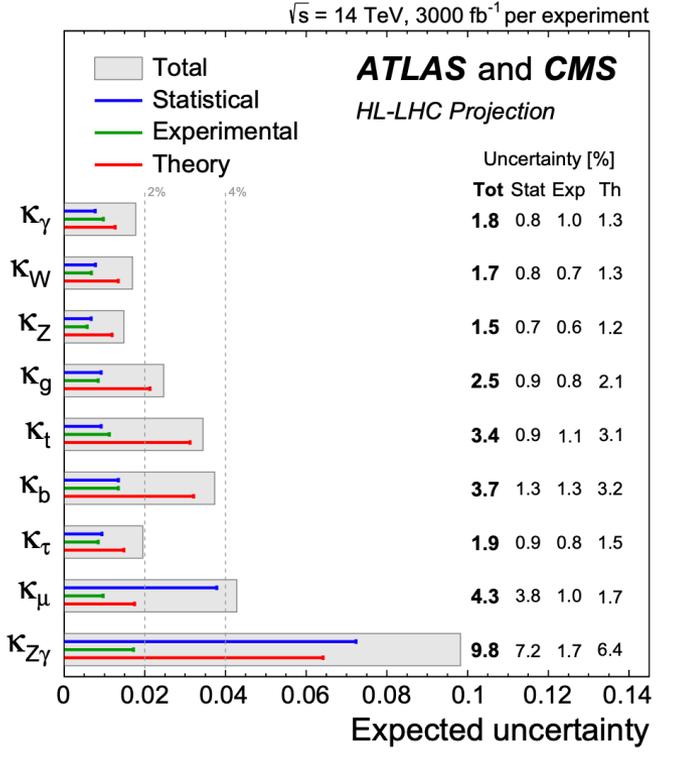
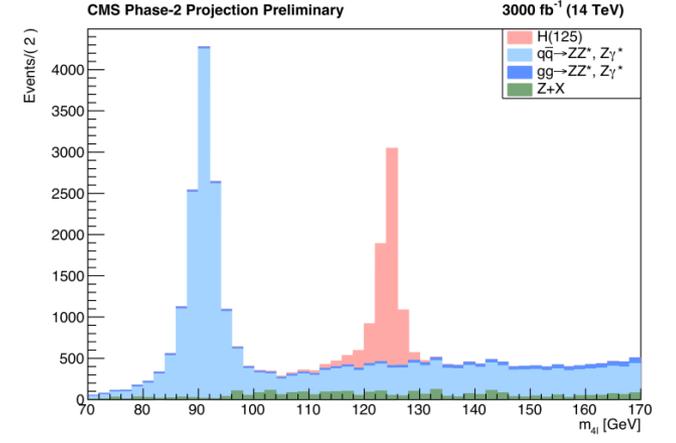
Beyond the SM

Higgs boson physics at the HL-LHC

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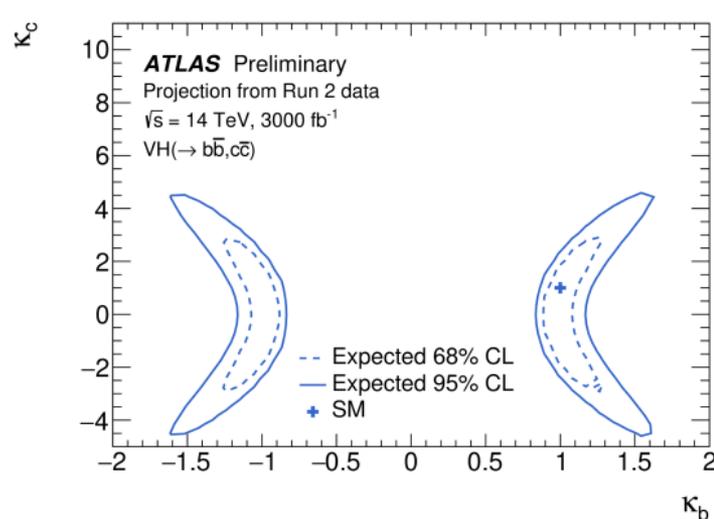
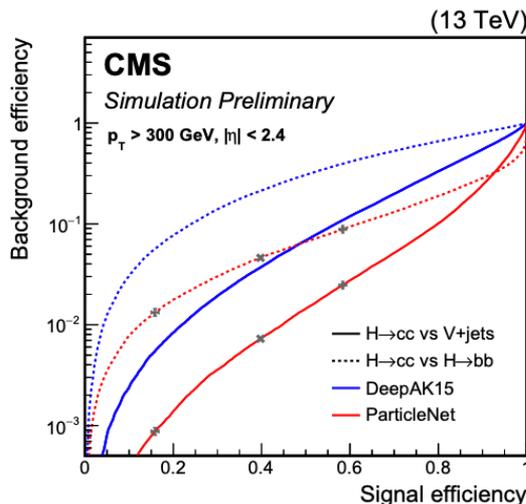
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- Precise measurements of mass and width
 - $H \rightarrow ZZ \rightarrow 4l$ and $H \rightarrow \gamma\gamma$
- Precise measurements of couplings to SM particles
 - Increased sensitivity to rare production and decay modes
- Evidence (or more) of Higgs self-coupling
- Measurements of differential distributions
 - Higgs p_T , Simplified Template Cross Sections, etc.



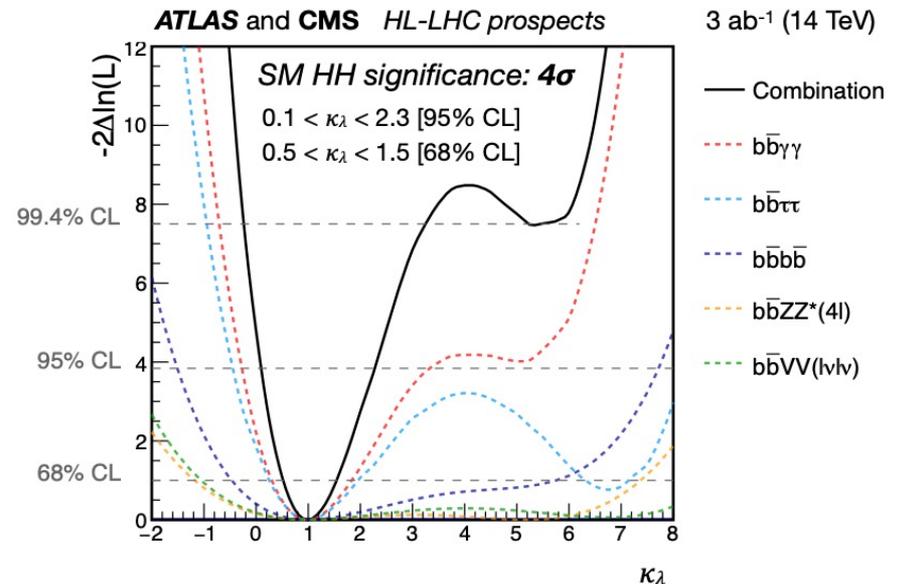
Higgs coupling to second generation fermions

- $H \rightarrow \mu\mu$ in ggF and VBF
 - Evidence in Run 2 at 3σ level. Project 5σ discovery of SM with $\sim 400 \text{ fb}^{-1}$
 -  New techniques brought us farther in Run 2 than we expected!
 -  Big gains from tracking upgrade in $m_{\mu\mu}$ resolution, extended η coverage
- $H \rightarrow cc$ in high p_T VH
 - Challenging search! rare process, large QCD background, charm tagging
 - Simultaneous measurement of $H \rightarrow bb$ and $\rightarrow cc$
 -   Gains from boosted jet reco, new charm-tagging algorithms



Di-Higgs production

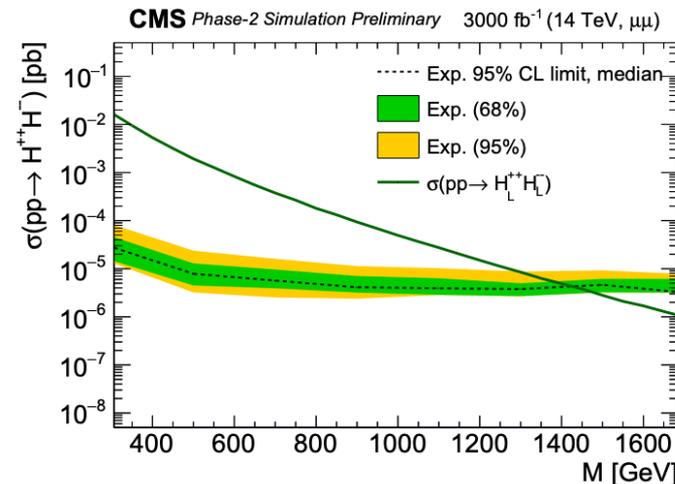
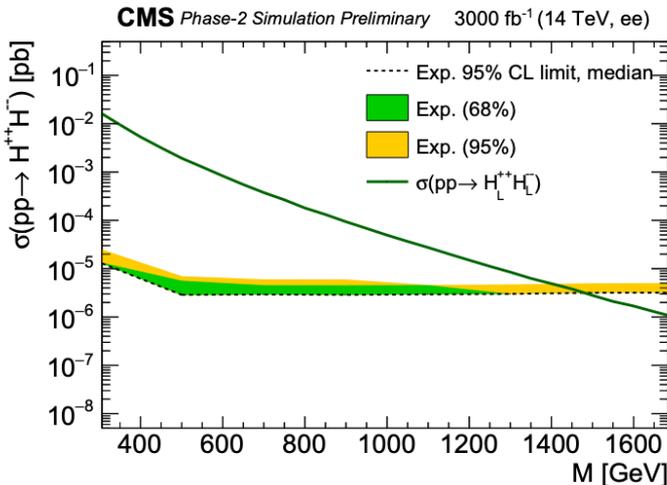
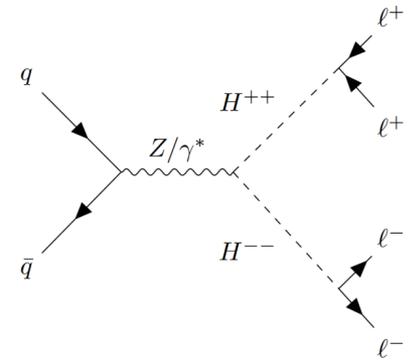
- Current projection: **4 σ combined sensitivity** to SM HH
 -  Constantly improving with analysis of current data
- Number of channels explored is constantly growing
 - New projections for decays HH \rightarrow $bb\gamma\gamma$, $WW\gamma\gamma$, $\tau\tau\gamma\gamma$, $bb\tau\tau$
 - New projection for $ttHH$ production with semi-leptonic top decay
- Pursuit of the **Higgs boson self-coupling**, κ_λ
 - Combined limits from ATLAS and CMS with full HL-LHC luminosity: $0.5 \leq \kappa_\lambda < 1.5$
 - Expect to exclude $\kappa_\lambda = 0$ at 95% CL



BSM Higgs

- Search for **doubly charged Higgs** ([new](#))

- Prediction of type II seesaw mechanism
- $H^{++} \rightarrow e^+e^+$ and $H^{++} \rightarrow \mu^+\mu^+$
- Nearly background-free search, especially at large H^{++} mass
- Expected exclusion $M < 1400$ GeV (compared to 750-870 GeV in Run 2)



- Another study of the seesaw mechanism at the HL-LHC can be found [here](#)

Standard Model physics at the HL-LHC

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- **Heavy flavor** and top quark physics

- Particle properties and rare processes

- **Precision electroweak** measurements

- $\sin^2 \theta_{\text{eff}}, m_W$

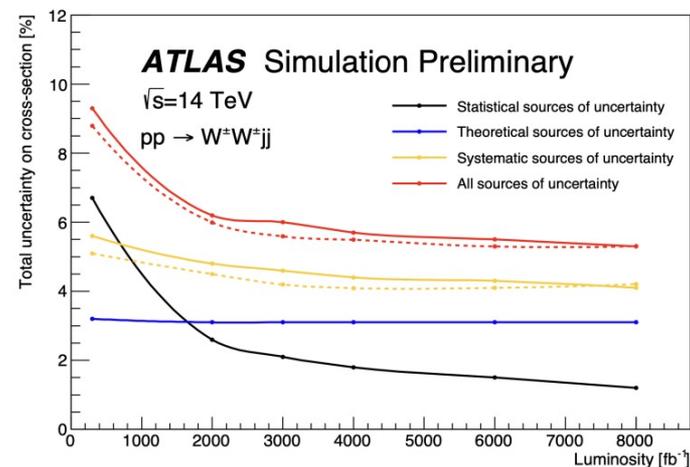
- Vector boson scattering

- **QCD** measurements

- Can constrain PDFs and the running of α_s

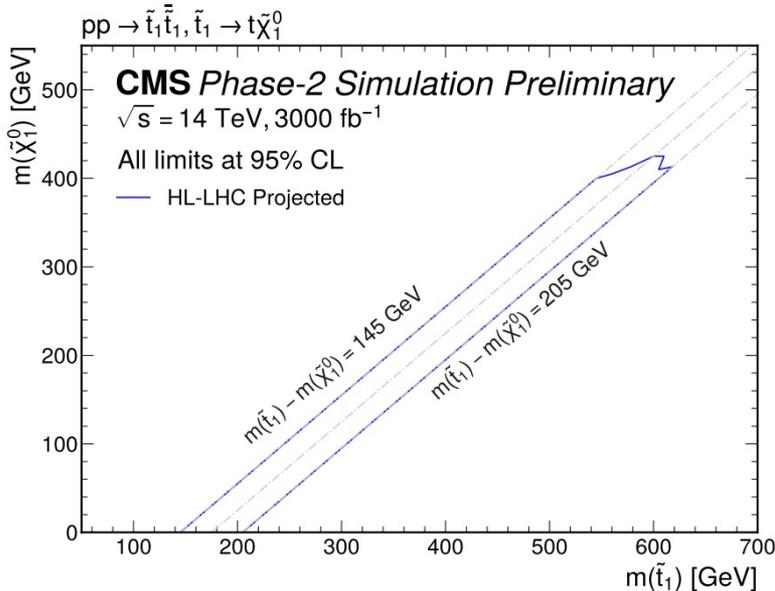
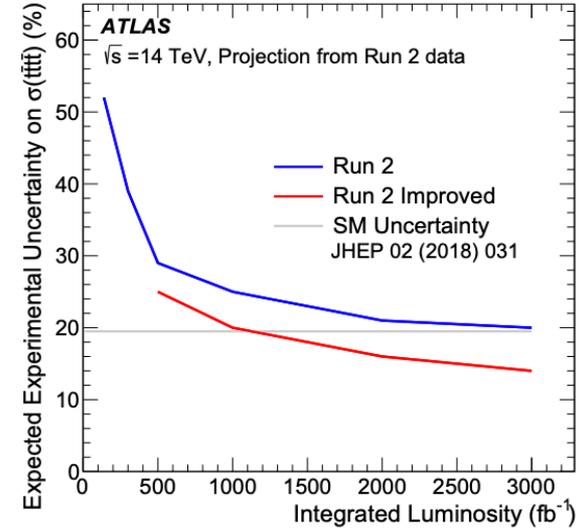
- Better understanding of backgrounds for many other analyses

- The HL-LHC as a **photon collider**



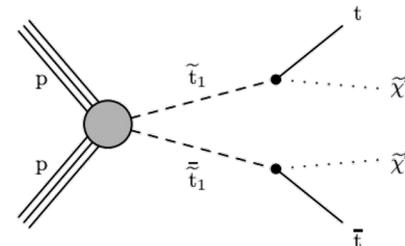
Top quark physics

- Projected measurement of the **four top** cross section
 - SM cross section = $16 \text{ fb}^{+18\%}_{-21\%}$
 - Enhancement predicted by many BSM processes (gluinos, scalar gluons, heavy boson + tt)
 - Expect $4\text{-}5\sigma$ sensitivity to SM process



- Top quark **spin correlations** ([new](#))

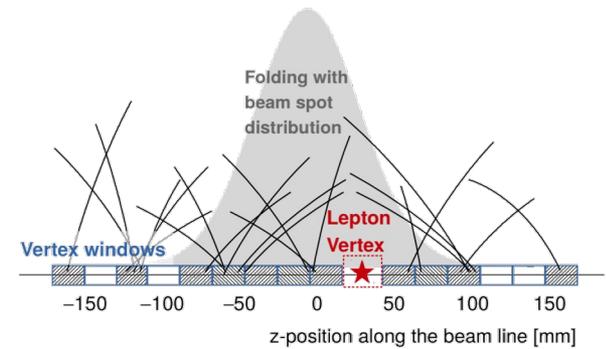
- Opposite sign $e\mu$ final state
- Systematics dominated by theory
-  Used in a multivariate search for stop squark pair production where $|\text{Im}(\text{stop}) - m(\chi_1^0)| \sim m(\text{top})$



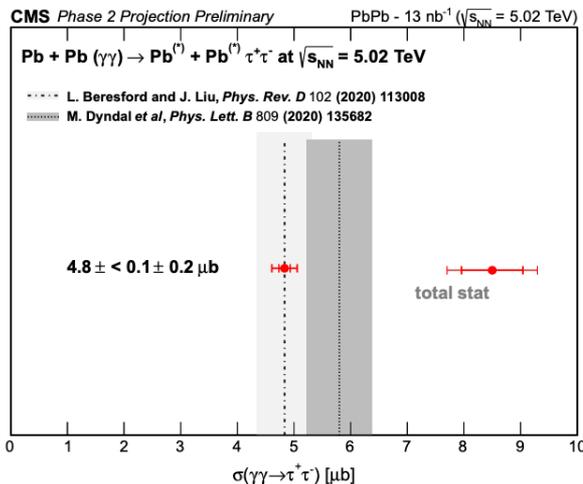
Photon-photon collisions

- **Exclusive WW** in pp ($\gamma\gamma \rightarrow WW \rightarrow e\nu \mu\nu$)

- Sensitive to anomalous gauge boson couplings
- Allow no tracks aside from W boson decay. Pileup makes this really hard!
-   Investigation of how to maximize detector upgrades for low p_T tracking, rejection of fake tracks, η coverage
- Expect total uncertainty reduction of $\sim 50\%$ at high dilepton mass



- Ultra-peripheral collisions of **$\gamma\gamma \rightarrow \tau\tau$ in Pb-Pb**



- Final state with $\mu + 3$ charged particles
- 4x more precise cross section at HL-LHC vs. Run 2
- Sensitive to anomalous magnetic moment of the tau $(g-2)_\tau$
-  With new analysis ideas & channels, could surpass existing constraints on $(g-2)_\tau$

Physics beyond the SM at the HL-LHC

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• Supersymmetry

– Strong SUSY is well constrained by the LHC, but HL-LHC probes smaller cross sections, mass splittings

– Potential increase of 20x in sensitivity to electroweak SUSY

• Heavy resonances

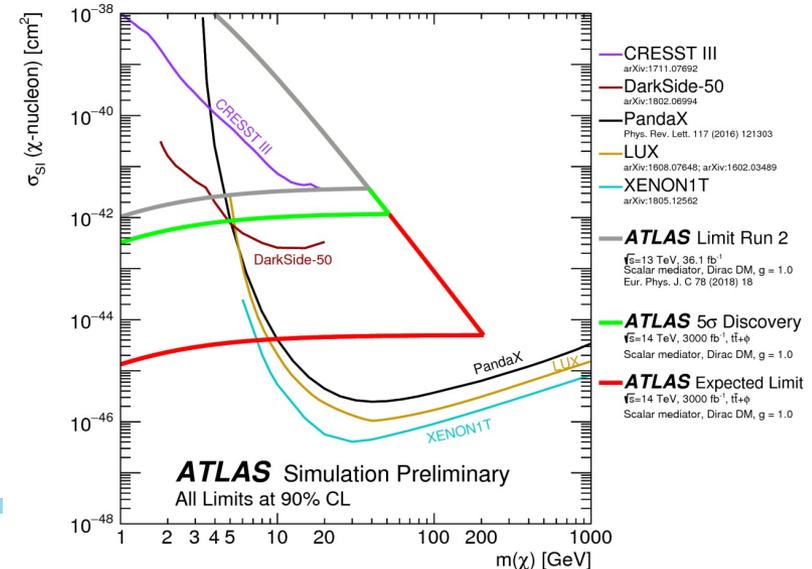
• Long-lived particles

–  Requires dedicated triggers and reconstruction algorithms

• Dark matter

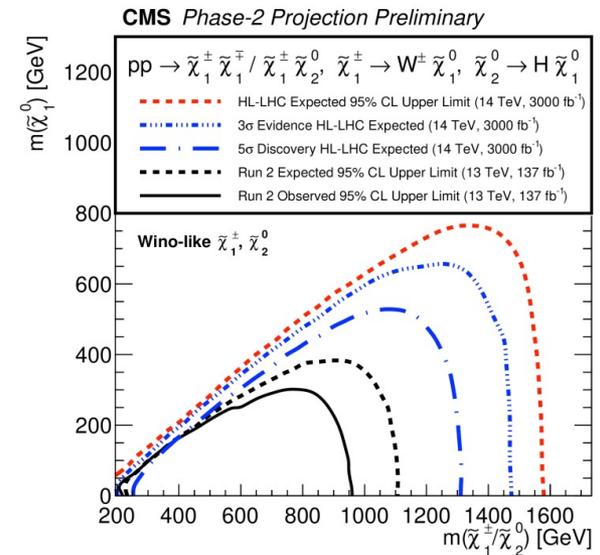
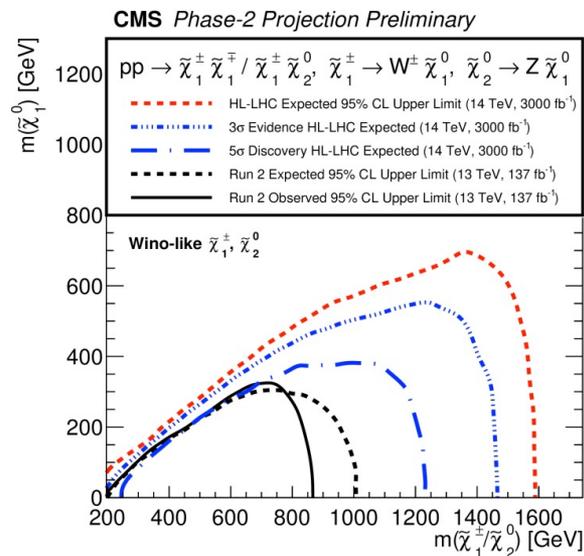
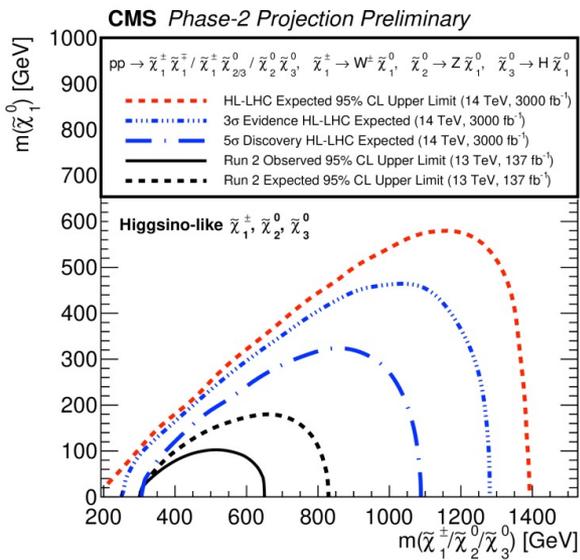
– Searches for DM accompanied by SM particle(s)

– Complementary to direct detection experiments



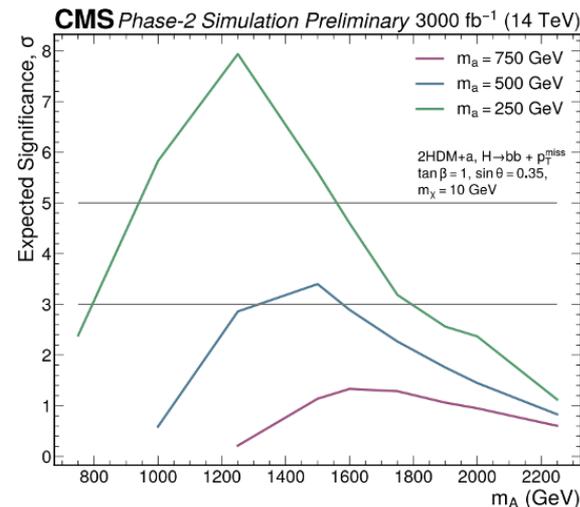
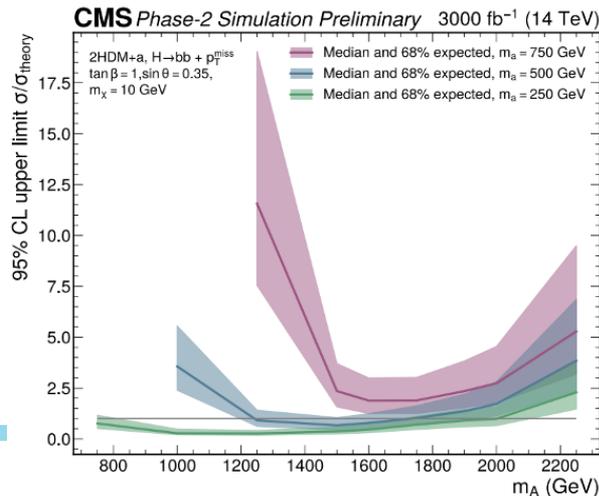
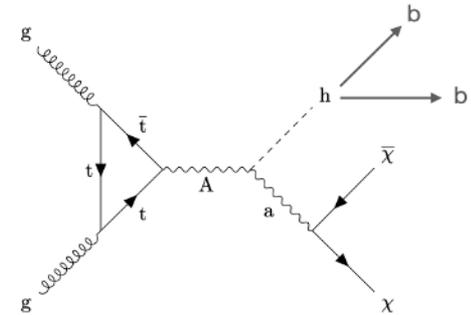
EWK SUSY with hadronic probes

- Pair production of NLSP: charginos, heavy neutralinos
 - $\chi_{1^+} \rightarrow W^+ \chi_{1^0}$, $\chi_{2^0} \rightarrow Z \chi_{1^0}$, $\chi_{2^0} \rightarrow H \chi_{1^0}$
 - Then hadronic W, Z, H decays (  boosted jet reco and flavor tagging)
- Coverage in NLSP mass extended by 600-750 GeV compared to Run 2



Dark matter with boosted mono-Higgs

- Boosted $H \rightarrow bb$ decay + missing transverse energy ([new](#))
 -   Gains from boosted jet tagging, improved vertexing (e.g. tracking, precision timing)
- Interpreted in type II 2HDM + additional light pseudoscalar boson (a)
 - For lighter a , get more boosted H and higher acceptance
 - Projections could exclude 1-2 TeV m_A for $m_a < 500$ GeV
 - 5σ discovery reach: m_A 1-1.6 TeV for $m_a = 250$ GeV

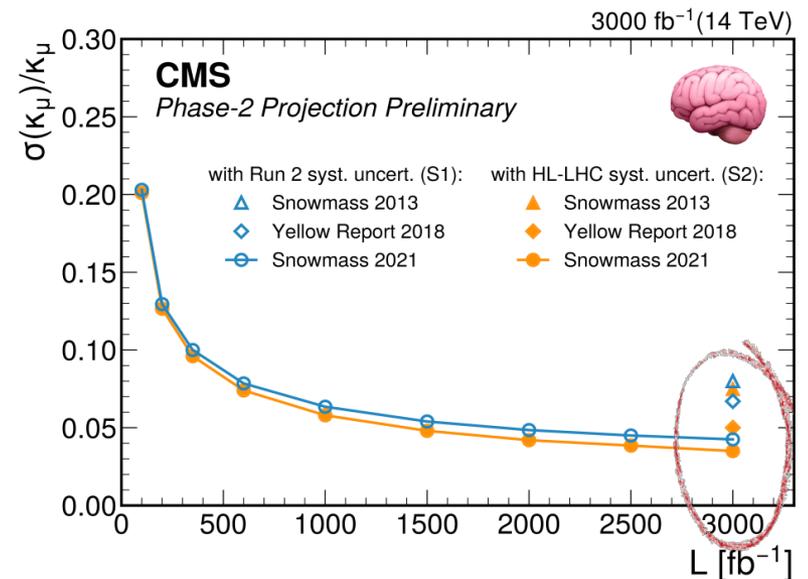


Conclusions

- The HL-LHC is the **immediate future** of physics on the energy frontier
- Along with accompanying upgrades, will be very powerful for physics across **Higgs**, **SM**, and **BSM**
 - Gains from high **luminosity, detector upgrades**, and new clever **algorithms**
- We've barely begun and are always improving!
- HL-LHC will provide a massive amount of new knowledge
 - Legacy will last for decades to come



The future is bright!



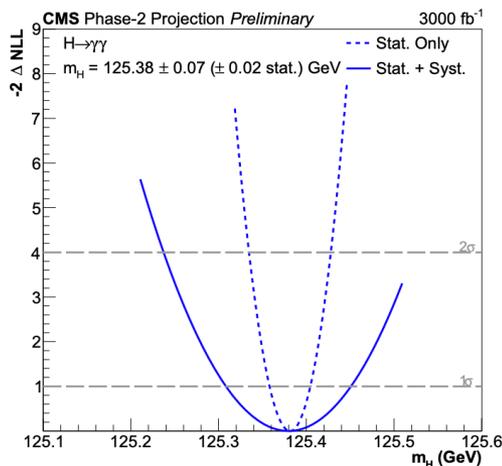
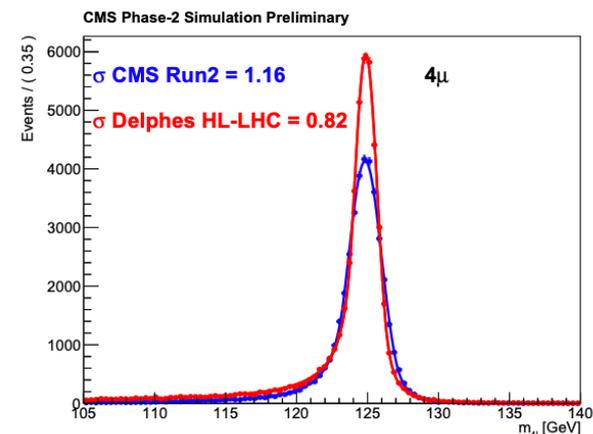
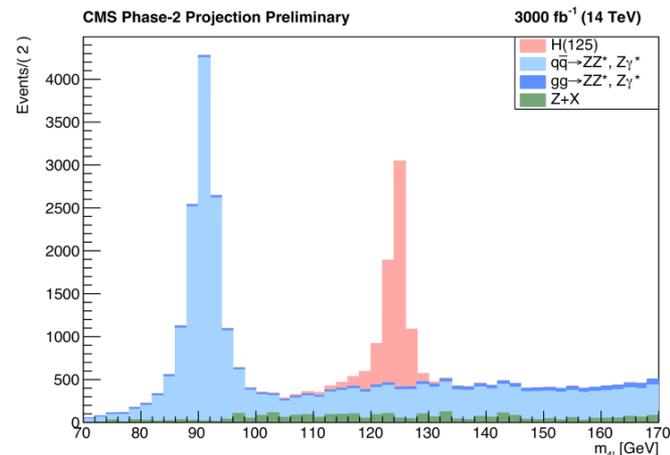
Extras

Higgs mass and width

- With run 2 data, combined $m_H = 125.38 \pm 0.14$ GeV

• $H \rightarrow ZZ \rightarrow 4l$

- Channels: $4e, 4\mu, 2e2\mu, 2\mu2e$
- $m_H = 125.38 \pm 0.03(\text{stat}) \pm 0.02(\text{sys})$ GeV
- $\Gamma_H < 0.09$ (0.18) GeV at 68% (95%) CL
-  Detector upgrades give better mass resolution, especially 4μ



• $H \rightarrow \gamma\gamma$

- $m_H = 125.38 \pm 0.02$ (stat) ± 0.07 (syst) GeV
- Benefits from  tracker and HGCAL upgrades,  photon energy calibration
- Systematics dominated by photon energy scale

BSM Higgs

- **Heavy Higgs** \rightarrow **WW**, $W \rightarrow e\nu$, $W \rightarrow \mu\nu$
 -  Multivariate analysis rejects background
 - Interpreted in several BSM scenarios, including MSSM and THDM
 - THDM run 2 limit at $m_H \sim 700$ GeV

